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# The Role of Debye Shielding in Plasma State of Matter

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**ABSTRACT:** Plasma is called the fourth state of matter after solid, liquid, and gas. It is a state of matter in which an ionized substance becomes highly electrically conductive to the point that long-range electric and magnetic fields dominate its behaviour. Plasma is an electrically charged gas. Because plasma particles have an electrical charge, they are affected by electrical and magnetic fields. This is the main difference between a gas and a plasma. Plasma is a form of matter in which many of the electrons wander around freely among the nuclei of the atoms. Plasma has been called the fourth state of matter, the other three being solid, liquid and gas. Normally, the electrons in a solid, liquid, or gaseous sample of matter stay with the same atomic nucleus.

**KEYWORDS:** Plasma, ionized, state, Debye, shielding

## I. INTRODUCTION

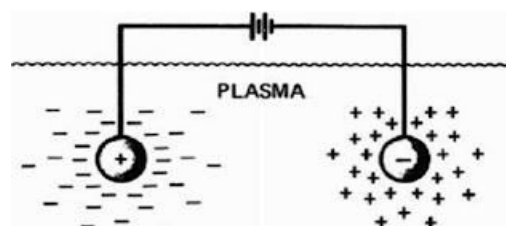
Plasma is one of the four common states of matter - solid, liquid, gas, and plasma. Plasma is an electrically charged gas. Plasma is superheated matter – so hot that the electrons are ripped away from the atoms forming an ionized gas. It comprises over 99% of the visible universe. In the night sky, plasma glows in the form of stars, nebulas, and even the auroras that sometimes ripple above the north and south poles. A plasma is an ionized gas consisting of positively and negatively charged particles with approximately equal charge densities. Plasmas can be produced by heating an ordinary gas to such a high temperature that the random kinetic energy of the molecules exceeds the ionization energy. Multiple beams of coloured plasma filaments can be seen oscillating within this plasma ball. A plasma ball is usually a clear glass sphere filled with a mixture of noble gases, such as neon and argon. A plasma is formed when voltage is applied to an electrode in the center of the glass sphere.

Plasma is the fourth state of matter, consisting of electrons, ions and neutral atoms, usually at temperatures above  $10^4$  degrees Kelvin. The sun and stars are plasmas; the earth's ionosphere, Van Allen belts, magnetosphere, etc., are all plasmas.

### Debye shielding

Plasmas generally do not contain strong electric fields in their rest frames. The shielding of an external electric field from the interior of a plasma can be viewed as a result of high plasma conductivity: i.e., plasma current generally flows freely enough to short out interior electric fields.

The Debye length is a most important physical parameter for the description of a plasma. It provides a measure of the distance at which the effect of the electric field of an individual charged particle is felt by other charged particles inside the plasma.





The charged particles arranged themselves in such a way as to effectively shield any electrostatic field within some distance of the order of Debye length. This shielding of the electrostatic field is a result of the collective effects of plasma particles.

$$\lambda_D = \left( \frac{\epsilon_0 kT}{n \cdot e^2} \right)^{\frac{1}{2}}$$

where,  $\epsilon_0$  = permittivity of free space

$k$  = Boltzmann constant

$e$  = Charge of electron

The Debye length can also be considered as a measure of the distance in which electric potentials can fluctuate in a plasma, which can be converted into electrostatic potential energy as thermal particle kinetic energy. The number of electrons ( $N_D$ ) inside a Debye sphere is given by

$$N_D = \frac{4}{3} \pi \lambda_D^3 n$$

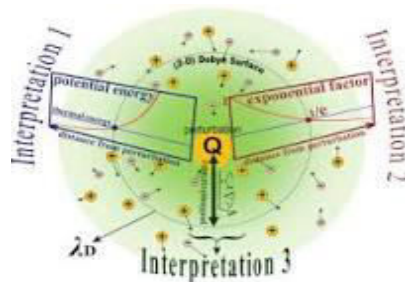
$$\Rightarrow N_D = \frac{4}{3} \pi \left( \frac{\epsilon_0 kT}{\frac{1}{n^3} \cdot e^2} \right)^{\frac{3}{2}}$$

The Debye shielding effect is a feature of all plasmas, although this does not occur in every medium that contains charged particles. An essential and obvious requirement for the existence of plasma is that the physical dimensions of the system are larger than the Debye length ( $\lambda_D$ ). Otherwise, there is just not sufficient space for the collective shielding effect to take place, and the collection of charged particle will not exhibit plasma behaviour.

### Debye shielding

One of the most elementary concepts in classical plasma physics is that of Debye shielding, which establishes the characteristic distance  $\lambda_D$  in which the electrostatic field from a charged test particle can be shielded by particles of the opposite sign.

### Formula for Debye length:



where  $L_D = (\epsilon kT/n e^2)^{1/2}$  is the Debye length and  $\epsilon$  is the permittivity,  $n$  is the electron density,  $e$  is the electronic charge,  $k$  is the Boltzmann constant,  $T$  is the temperature, and  $V_s$  is the potential at the surface.

### Calculation of Debye length in plasma

In traditional, electron/ion plasmas, it is often only electrons that participate in the screening (because ions move too slowly), so the ion term is dropped, and the Debye length is given by the electron term only:

$$\lambda_D = \left( \frac{\epsilon_0 kT}{n \cdot e^2} \right)^{\frac{1}{2}}$$

The Debye (symbol: D) is a CGS unit (a non-SI metric unit) of electric dipole moment named in honour of the physicist Peter J. W. Debye. It is defined as  $10^{-18}$  stat coulomb-centimeters.

### principle of shielding effect

The shielding effect describes how electrons closer to the nucleus "shield" the electrons farther away from the positive charge of the nucleus.



## II. TYPES OF PLASMA

Over 100 different types of plasma protein exist but they can be grouped into 3 fractions;

1. Plasma Albumin,
2. Plasma Globulin and
3. Fibrinogen.

### Functions of Plasma:

- Redistributing water where your body needs it.
- Delivering hormones, nutrients and proteins to parts of your body and helping to exchange oxygen and carbon dioxide.
- Supporting blood vessels from collapsing or clogging.
- Maintaining blood pressure and circulation.

### Classification of Plasma:

Based on the relative temperatures of the electrons, ions and neutrals, plasmas are classified as thermal or non-thermal. Thermal plasmas have electrons and the heavy particles at the same temperature i.e., they are in thermal equilibrium with each other.

### Review of Related Literature:

Irving Langmuir introduced the term plasma in 1923 while investigating electric discharges. In 1929 he and Lewi Tonks, another physicist working in the United States, used the term to designate those regions of a discharge in which certain periodic variations of the negatively charged electrons could occur.

### Plasma is charged gas molecules

A plasma is created when one or more electrons are torn free from an atom of gas. Atoms that have lost some or all of their negatively charged electrons are called ions. An ionized atom has a positive charge because it is missing electrons, but still contains positively charged protons and neutrons (with no charge) in its atomic nucleus. A plasma is generally a mix of these positively charged ions and negatively charged electrons.

Most plasmas are created when extra energy is added to a gas, which can occur when gases are heated to high temperatures. Atoms in a hot gas are moving so fast that electrons can be knocked loose when they collide with each other. High energy photons from the Sun, including gamma rays, X-rays, or ultraviolet radiation, can create plasma by knocking electrons away from their atoms. High-voltage electricity, such as from lightning strikes, can also create plasmas.

### Plasma is the most common state of matter in the universe.

Matter in the plasma state is far more abundant than matter in the liquid, solid, or gaseous states. 99 percent of all matter, other than the mysterious "dark matter" that astronomers have been puzzling over, is plasma. Most of the matter in the Sun and other stars exists in a plasma state.

Though common in the universe, plasma is less abundant on Earth. Regions of Earth's atmosphere called the ionosphere contain some plasma that is created through ultraviolet radiation from the Sun. The upper layers of Earth's atmosphere, the thermosphere and exosphere (and to a lesser extent the mesosphere), also contain plasma mixed in with atoms and molecules of different gases. Above the atmosphere, Earth is surrounded by a magnetic field called the magnetosphere. Most of the particles in the magnetosphere are ionized plasma.

### Plasma creates glowing light seen in the sky

The green lights above Earth's surface are the aurora (northern lights and southern lights), as seen from the International Space Station on July 25, 2010. Auroras primarily occur in Earth's thermosphere, which is an upper layer of the atmosphere.

Plasma in Earth's magnetosphere sometimes flows along Earth's magnetic field towards the polar regions, creating the colourful light shows in the sky which we call the aurora, or northern and southern lights. These beautiful displays occur when energetic plasma particles collide with gases in the atmosphere, causing them to glow.



Solar prominences, which are giant loops of glowing matter suspended above the Sun, are another example of beautiful natural light shows created by plasmas. Though invisible to the eye, the solar wind that is constantly streaming out from the Sun contains large amounts of plasma along with various types of solar energy.

**Plasma can be created artificially**

Some plasmas are created artificially by humans. Electricity in fluorescent lights creates a plasma. Colourful neon lights, often used in signs, also use electricity to convert gas molecules into glowing plasma. Certain types of flat-screen televisions make use of plasma as well.

**The principle of shielding effect:**

The shielding effect describes how electrons closer to the nucleus shield the electrons farther away from the positive charge of the nucleus.

$$\delta\Phi(r) = \frac{q}{4\pi\epsilon_0 r} e^{-\sqrt{2}r/\lambda_D}$$

**Debye Shielding**

Plasmas generally do not contain strong electric fields in their rest frames. The shielding of an external electric field from the interior of a plasma can be viewed as a result of high plasma conductivity: i.e., plasma current generally flows freely enough to short out interior electric fields. However, it is more useful to consider the shielding as a dielectric phenomenon: i.e., it is the polarization of the plasma medium, and the associated redistribution of space charge, which prevents penetration by an external electric field. Not surprisingly, the length-scale associated with such shielding is the Debye length.

Let us consider the simplest possible example. Suppose that a quasi-neutral plasma is sufficiently close to thermal equilibrium that its particle densities are distributed according to the Maxwell-Boltzmann law,

$$n_s = n_0 e^{-e\phi/T}$$

Where  $\phi(r)$  is the electrostatic potential, and  $n_0$  and  $T$  are constant. From  $e_i = -e_e = e$ , it is clear that quasi-neutrality requires the equilibrium potential to be a constant. Suppose that this equilibrium potential is perturbed, by an amount

$\delta\Phi$ , by a small, localized charge density  $\delta\rho_{ext}$ . The total perturbed charge density is written

$$\delta\rho = \delta\rho_{ext} + e(\delta n_i - \delta n_e) = \delta\rho_{ext} - 2e^2 n_0 \delta\Phi/T$$

Thus, Poisson's equation yields

$$\nabla^2 \delta\Phi = -\frac{\delta\rho}{\epsilon_0} = -\left(\frac{\delta\rho_{ext} - 2e^2 n_0 \delta\Phi/T}{\epsilon_0}\right),$$

which reduces to

$$\left(\nabla^2 - \frac{2}{\lambda_D^2}\right) \delta\Phi = -\frac{\delta\rho_{ext}}{\epsilon_0}$$

If the perturbing charge density actually consists of a point charge  $q$ , located at the origin, so that  $\delta\rho_{ext} = q\delta(r)$ , then the solution to the above equation is written

$$\delta\Phi(r) = \frac{q}{4\pi\epsilon_0 r} e^{-\sqrt{2}r/\lambda_D}$$

Clearly, the Coulomb potential of the perturbing point charge  $q$  is shielded on distance scales longer than the Debye length by a shielding cloud of approximate radius  $\lambda_D$  consisting of charge of the opposite sign.



### **Debye screening in plasma**

In plasma physics, electric-field screening is also called Debye screening or shielding. It manifests itself on macroscopic scales by a sheath (Debye sheath) next to a material with which the plasma is in contact. The screened potential determines the inter atomic force and the phonon dispersion relation in metals.

### **Debye length of plasma**

In plasma physics, the Debye length, named after the Dutch physical chemist Peter Debye, is the scale over which mobile charge carriers (e.g., electrons) screen out electric fields in plasmas and other conductors. In other words, the Debye length is the distance over which significant charge separation can occur.

### **Usage of Debye**

The Debye is still used in atomic physics and chemistry because SI units have until recently been inconveniently large. The smallest SI unit of electric dipole moment is the quetocoulomb-metre, which corresponds to roughly 0.3 D.

### **An example of a plasma matter**

Plasma is thus also described as the fourth aggregate state of matter: the gas atoms split into their constituent components – electrons and nuclei. Everyday examples of plasmas include:

plasma columns in neon tubes,  
electric sparks and  
the plasma filament in a lightning flash.

### **Usage of plasma:**

For many people with rare diseases and chronic conditions, plasma-based therapies are the only way to treat their condition or disease. Plasma is also given to trauma patients and burn victims to help with blood clotting and to boost their blood volume, which can prevent and treat shock.

### **Usage of plasma in daily life**

Plasma is the fourth state of matter, consisting of electrons, ions and neutral atoms, usually at temperatures above  $10^4$  degrees Kelvin. The sun and stars are plasmas; the earth's ionosphere, Van Allen belts, magnetosphere, etc., are all plasmas.

Plasma is being used in many high-tech industries. It is used in making many microelectronic or electronic devices such as semiconductors. It can help make features on chips for computers. Plasma is also used in making transmitters for microwaves or high temperature films.

### **Existence of plasma on Earth**

There are also plasmas here on Earth, ranging from the inside of a nuclear fusion reactor to a candle flame. In the Space Plasma Physics Group, we study plasmas in the Earth's magnetosphere and the solar wind, and what happens when they interact.

### **Classification of plasma**

Based on the relative temperatures of the electrons, ions and neutrals, plasmas are classified as thermal or non-thermal. Thermal plasmas have electrons and the heavy particles at the same temperature i.e., they are in thermal equilibrium with each other.



### Functions of plasma

- Redistributing water where your body needs it.
- Delivering hormones, nutrients and proteins to parts of your body and helping to exchange oxygen and carbon dioxide.
- Supporting blood vessels from collapsing or clogging.
- Maintaining blood pressure and circulation.
- The Debye sheath (also electrostatic sheath) is a layer in a plasma which has a greater density of positive ions, and hence an overall excess positive charge, that balances an opposite negative charge on the surface of a material with which it is in contact. The thickness of such a layer is several Debye lengths thick, a value whose size depends on various characteristics of plasma (e.g., temperature, density, etc.).

A Debye sheath arises in a plasma because the electrons usually have a temperature on the order of magnitude or greater than that of the ions and are much lighter. Consequently, they are faster than the ions. At the interface to a material surface, therefore, the electrons will fly out of the plasma, charging the surface negative relative to the bulk plasma. Due to Debye shielding, the scale length of the transition region will be the Debye length. As the potential increases, more and more electrons are reflected by the sheath potential. An equilibrium is finally reached when the potential difference is a few times the electron temperature.

The Debye sheath is the transition from a plasma to a solid surface. Similar physics is involved between two plasma regions that have different characteristics; the transition between these regions is known as a double layer, and features one positive, and one negative layer.

Sheaths were first described by American physicist Irving Langmuir. Langmuir and co-author Albert W. Hull further described a sheath formed in a thermionic valve.

### The concept of Debye shielding

One of the most elementary concepts in classical plasma physics is that of Debye shielding, which establishes the characteristic distance  $\lambda_D$  in which the electrostatic field from a charged test particle can be shielded by particles of the opposite sign.

### Occurrence of Debye Shielding

Shielding is caused by the combination of partial neutralization of nuclear charge by core electrons, and by electron-electron repulsion. The amount of charge felt by an electron depends on its distance from the nucleus.

unit value of Debye

Prove 1 Debye =  $10^{-18}$ esu cm =  $3.335 \times 10^{-30}$ C-m (coulomb meter).

What is the SI unit of 1 Debye?

Hence, 1 debye =  $10^{-18}$ esu cm =  $3.335 \times 10^{-30}$  C m is proved

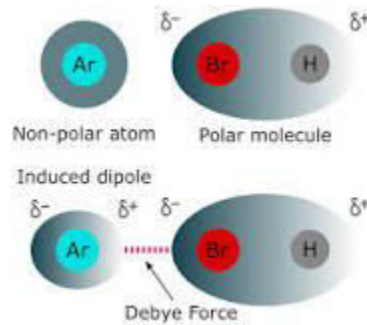
### The most effective shielding

Lead has long been considered "the element of choice" for radiation shielding due to its attenuating properties. Lead is a corrosion-resistant and malleable metal. Lead's high density (11.34 grams per cubic centimeter) makes it an effective barrier against X-ray and gamma-ray radiation. 01-Dec-2022

### Functions of shielding

Thermal shielding is applied for protection of radiation heat, where the shield must keep the heat losses to the wall low. This is the main function in tool machines. In component applications, water-cooled shields can be applied to cool the substrate and as such to enable an increased deposition rate.

**Examples of Debye**

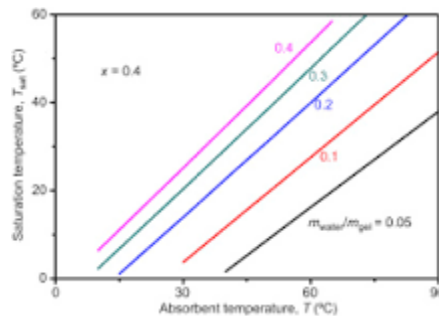


An example of Debye force is the intermolecular force of attraction between hydrogen bromide and argon. HBr, being a polar molecule, possesses a permanent dipole moment due to the electronegativity difference between hydrogen and bromine.

**Location of Debye**

Debye is a lunar impact crater that is located in the northern hemisphere on the Moon's far side, as seen from the Earth. It lies to the south of the crater Chappell, to the southwest of the walled plain Rowland, and to the east of D'Alembert.

**Another name for Debye forces**



Generally known as 'van der Waals force' these are the dispersion force (London interaction) the induction force (Debye interactions), and the orientation force (Keesom interactions).

**Debye force**

Debye forces are caused by the interactions between permanent dipoles and other atoms/molecules, which results in the formation of induced dipoles. For example, an induced dipole can be formed from the repulsive forces between electrons (belonging to a molecule) and a permanent dipole.

**III. DIFFERENT TYPES OF RADIATION SHIELDING MATERIALS**

- Traditional Lead Shielding.
- Lead Composite Shielding.
- Lead-Free Shielding.
- Why does Debye length increase with temperature?
- What determines this size  $\lambda_D$ ? If temperature increases, the effects of entropy and temperature also increase. We'd expect the screening cloud to spread out due to the increased molecular motion. Therefore,  $\lambda_D$  should increase as T increase





### Debye shielding advantages and disadvantages

The inappropriate location of shielding is among the risks, for example obscuring the anatomy and leading to increased dose, resulting in re-takes, or interfering with automatic exposure control. Using shielding in CT scans can also cause artefacts and noise. Debye theory of specific heat of solids Debye treated the solid as a continuous elastic body in which the vibrations of the atoms generate stationary waves. According to Debye, the atoms in a solid do not vibrate independently with same frequency. Additionally, shielding can help prevent people from being exposed to electromagnetic radiation, which can be harmful to health. The primary drawback of shielded cables is that they can be more expensive than unshielded cables. This is because the extra shielding material adds to the manufacturing cost of the cable.

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